

The Selection of a Radiation-Tolerant DAC for the LHC (Part II: CMOS Technology)

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Abstract. - Total dose & neutron tests on commercial CMOS digital-to-analog converters have been carried out. These results are related to those ones presented in the previous paper. This kind of devices is much more sensitive to ionizing radiation than to neutrons. That radiation changes the value of the MOSFET threshold voltage and this can put digital circuits out of action. In this case, the gradual destruction of the digital inputs was observed as a diminution of the output voltage levels. Also, the gamma radiation generates leakage currents that increase the consumption. Due to these converters tolerated less total radiation dose, their use in the LHC has been refused and the fast bipolar technology converters will be employed.

Index Terms.- COTS, digital-to-analog converters, radiation tolerance, CMOS technology, LHC.

I. CMOS & BIPOLAR DEVICES

As shown in the previous paper, a bipolar digital-to-analog converter was selected to be used in the Large Hadron Collider (LHC). However, before coming to this conclusion, some CMOS converters were tested. The CMOS technology has some advantages upon the bipolar one: Better integration possibility, which allows to build smaller devices; Lower consumption, because of the device does not need any supply current in static behaviour while a typical bipolar converter requires several miliamperes all the time. Finally, CMOS converters are usually cheaper than bipolar ones.

The neutron radiation hardly affects the CMOS devices. They work using majority carriers so the only important matter is the resistivity increase. However, this is only problematic on power devices. Unfortunately, the ionizing radiation strongly damages the CMOS devices through two mechanisms: The ionizing radiation creates positive charges inside the MOSFET gate insulator that modify the threshold voltage and can put the transistors out of action. On the other hand, the epitaxial SiO₂ stores positive charges and this leads to the creation of leakage currents, which affect the bias point and increase the consumption.

This damage is originated by ionizing radiation, either gamma, X rays or charged particle as cosmic rays.

Also, these particles can damage the device on other ways. A charged particle can fly through a free-of-charge zone leaving a trail of electrons and holes. If the voltage difference between the empty extremes is quite high and if the particle trail is enough large, a brief short-circuit is provoked. Also, the charge generated by this particle can trigger parasitic SCR of the device. This event can completely destroy the converter or, at least, damage it seriously. Good works are [1, 2], where the previous subject is widely developed.

II. TESTED CMOS CONVERTERS

The selected devices to be tested were AD7541AKN, AD7545AKN & DAC8222A, from Analog Devices, and MX7541AKN, from Maxim. All of them were 12-bit parallel input converters with current output and external voltage reference. They needed an operational amplifier connected to the output, which was placed outside the reactor. The AD7541AKN & MX7541AKN were two versions of the same model of monolithic multiplying converter. The other converters are monolithic multiplying too but they have a latch, which sets the input. The measure system was described in the previous paper.

III. RESULTS

A) AD7541AKN & MX7541AKN

The AD7541AKN converter received a total radiation dose of $2.77 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ and 1300 Gy. In the beginning, the offset and gain errors remain constant up to $7.5 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 350 Gy. From this value on, the offset error starts growing with a high slope (fig. 1). The evolution of the gain error is similar to the offset error although the values are negative. Meanwhile, the relative number of bits (fig. 2) keeps stable up to $3.5 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 160 Gy and starts to decrease until becoming 7.5 at $9 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 415 Gy. From this value on, its value grew for a time. Moreover, during the stand-by phases,

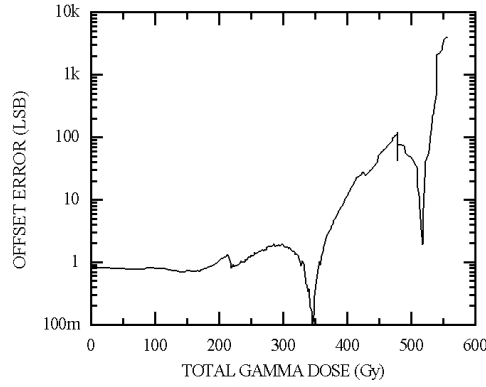


Fig. 1: The evolution of the offset error in the AD7541AKN converter

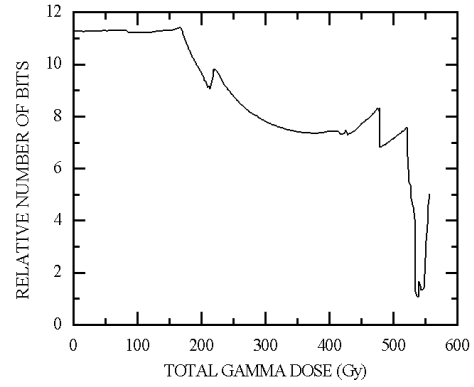


Fig. 2: AD7541 relative number of bits. Sharp jumps belong to the stand-by times.

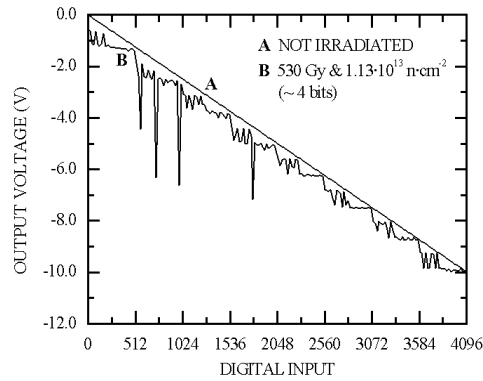


Fig. 3: Input-Output function on AD7541AKN. The response absence of the inputs causes the apparition of levels with a constant value.

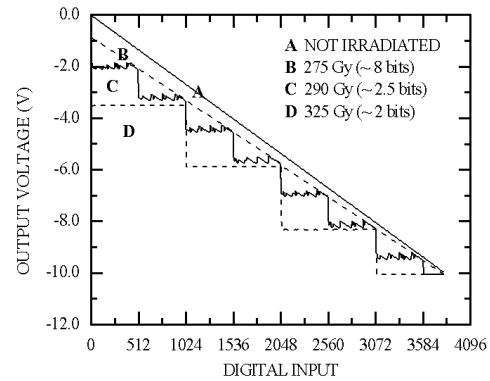


Fig. 4: Input & output relationship on MX7541AKN. Some lines are dashed for a higher clarity. The evolution was similar to AD7541AKN. This graph is very interesting since the bit loss is clear.

the annealing makes the number of bits be lower. When the total radiation dose is $1.2 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ & 565 Gy, the converter stops working. The relationship between digital input and output are shown in fig. 3. Unlike the DAC703KH, the loss of bits is caused by a transformation of the initial straight line into a stair function. On the other hand, there is a little increase of the current provided by the digital supply. Initially, it was 0 μA and, after the irradiation, 0.75 μA . The MX7541AKN evolution is similar to the previous one. They have the same design but different companies manufacture them. A difference is that this converter has got a smaller tolerance. The offset & gain errors starts growing at $2.5 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 100 Gy and the converter were destroyed at $8.5 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ and 325 Gy. Fig. 4 shows the evolution of the relationship between the input and the output during the irradiation.

B) AD7545AKN

This device received a total radiation dose of $2.26 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ & 1080 Gy. It is similar to AD7541 but has latches between the inputs and the internal converter. The offset error remains constant up to $3.6 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 175 Gy and, then, it begins increasing (fig. 5).

From $5 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 240 Gy on, the offset error grows in a linear way ($\sim 4 \text{ LSB/Gy}$ or $194 \text{ LSB}/10^{12} \text{ n}\cdot\text{cm}^{-2}$). The evolution of gain error is similar to offset but its value is negative. The converter is destroyed at $1.9 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ & 910 Gy.

The relative number of bits does not shift from 10.5 until reaching $3.6 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ & 175 Gy. From this value on, it starts decreasing softly until becoming 4.6 at the moment of the converter destruction (fig. 6). The accuracy loss is related to the disappearance of output voltage levels on the converter (fig. 7). The only consumption increase was observed in the digital supply. The supplied current grew from 0 A to 0.67 μA .

C) DAC8222A

This CMOS converter received a total radiation dose of $2.26 \cdot 10^{13} \text{ n}\cdot\text{cm}^{-2}$ & 1080 Gy. This is the least tolerant converter because the offset error begins rising just at $10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 48 Gy (fig. 8). Like the other CMOS converter, the evolution of the gain error is similar to the offset error but it is negative. The relative number of bits decreases softly from 10.2 down to 6.2 at $8.4 \cdot 10^{12} \text{ n}\cdot\text{cm}^{-2}$ & 400 Gy (fig. 9). Suddenly, a quick fall happens

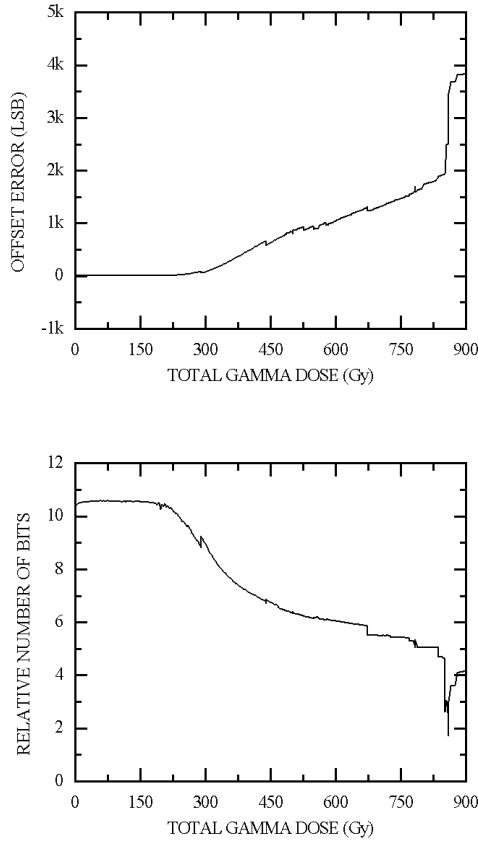


Fig. 5-6: Offset error & relative number of bits of AD7545AKN

and, a bit later, the converter stopped working. Like the other converter, the diminution of this parameter is a consequence of the destruction of the inputs (fig. 10). Finally, the increase of the current of the digital supplied was $0 \text{ A} \rightarrow 0.82 \mu\text{A}$.

IV. DISCUSSION

All the tested converters belong to the monolithic multiplying kind. The differences are the technology and the placement of latches in the input stage. Fig. 11 shows the basic design of a converter of this kind [3]. The resistances are of semiconductor type and the switches are built with CMOS transistors. So, unlike the case of bipolar technology transistors, the action of the radiation on the device can be easily understood.

The gamma radiation shifts the threshold voltage of the MOSFET [4]. In PMOS, this voltage decreases since the beginning but, in NMOS, the behaviour is quite different. There are two opposite mechanisms that shift the NMOS threshold voltage: Positive charge trap inside the insulator and negative charge trap on the semiconductor surface states. The competition between both mechanisms depends on the dose rate. Generally, the threshold voltage starts decreasing and it can become lower than 0 V due to the charge trap. Next, the trapped

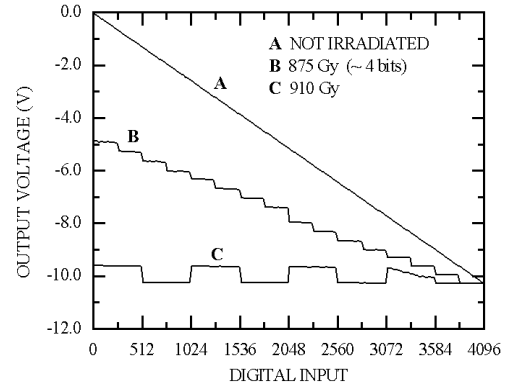


Fig. 7: The AD7545AKN output voltage as a function of the digital input. The conversion of the initial straight line into a stair-shaped function is clear. The number of levels of B is 16. On the other hand, the difference between the two main values of C is $V_{REF}/16$.

positive charges move to a zone close to the $\text{SiO}_2\text{-Si}$ interface and creates new surface states that trap electrons and compensate the positive charge. At this time, the threshold voltage value becomes the initial one. Then, the number of trapped electrons becomes larger than positive charges and the threshold voltage starts growing and can rise beyond the positive supply.

The NMOS & PMOS threshold voltages have changed so the digital networks can stop working [5]. The total radiation dose depends on the characteristics of the transistors (size, dielectric type, bias, dose rate). The response absence of the inputs is caused by the work incapacity of the switches and we believe that the radiation closes all the switches. Independently from the input value, the switches behave just like there was a digital “1” in the input. When the total radiation dose reaches a critical value, an input switch stops working. This radiation value depends on the internal characteristics of the switches so the absence of their switch ability is random. E. g., on the AD7545AKN converter, the most tolerant inputs were 2, 3, 4 & 5 and the only reason was the difference among the transistors caused by the manufacturing conditions. On the other hand, the strange behaviour of the threshold voltage of the NMOS explains why there is an increase of the relative number of bits of AD7541AKN according to the total radiation dose. A switch that could not work starts doing it again since the NMOS threshold voltages come back to have values that allow the switching. However, the NMOS threshold voltage continues growing and the switch cannot work. Then, the converter loses accuracy.

On the other hand, the gain error of all the converters is similar to the offset error. There is an easy explanation. Due to all the effective inputs are “1”, the 4095 output has to be always correct. The calculus of the error gain needs this value and the offset error:

$$G.E. = \frac{OUT(4095) - OUT(0)}{L.S.B.} - (2^{12} - 1)$$

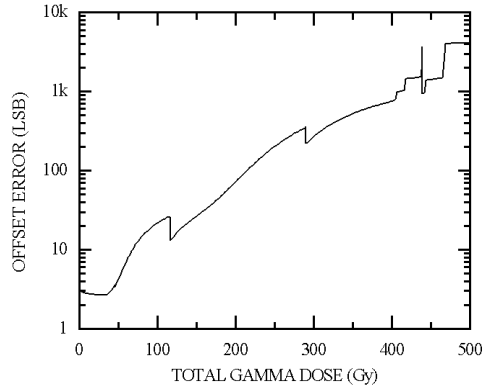


Fig. 8: The offset error of DAC8222A

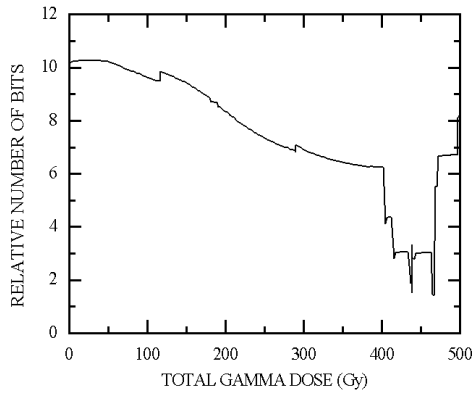


Fig. 9: The relative number of bits of DAC8222A

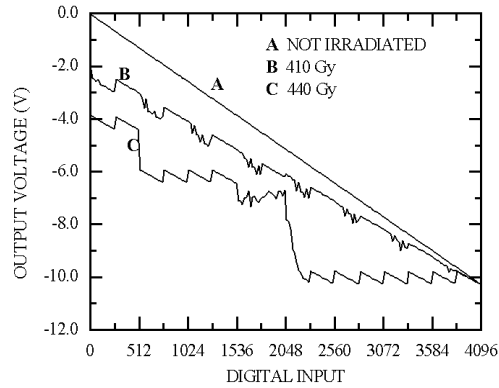


Fig. 10: The input-output relationship on DAC8222A

Due to the first value hardly changes, the only error source must be $OUT(0)/LSB$. However, this is the definition of the offset error so the relationship between gain & offset errors is explained. The shift of the threshold voltage is not the only cause of the destruction of the converters. Also, leakage currents appear among the internal transistor. This is the cause of the increase of the consumption. The required current is in the order of the microampere on all this devices. These values are far from those one measure on other CMOS devices, where the consumption can reach several milliamperes,

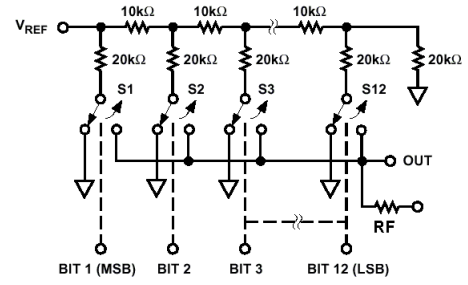


Fig. 11: The basic structure of a monolithic multiplying converter. Other converters have a latch between the input and the switch.

but the growth of the consumption (and, therefore, the leakage current apparition) is unquestionable. The highest current supplied by the converter outputs is about 600-700 μA . So, 1 L. S. B. ~ 140 nA and the parasitic current can affect the resolution of the least significative bits.

The final matter is the way that the neutron damages the converter in. The only mechanism is the growth of the semiconductor resistances: The internal resistors are laser-trimmed to increase the converter accuracy and the neutron radiation modifies the value of the resistances. Therefore, the converter loses accuracy and the relative number of bits gets lower.

V. CONCLUSION

Some CMOS digital-to-analog converters were tested under neutron & gamma radiation. The radiation affects them in the following ways: Increase of the offset error, loss of accuracy and a small growth of the consumption. The damage is mainly caused by the ionizing radiation, which shifts the MOSFET threshold voltage and creates leakage currents.

Neither of the converters could tolerate more than $1.9 \cdot 10^{13}$ $n \cdot cm^{-2}$ & 910 Gy although the damage appeared at much lower total doses. Comparing these results to those ones shown in the previous paper, we conclude that the CMOS digital-to-analog converters are less tolerant than those ones built in fast bipolar technology.

VI. REFERENCES

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